Measurements Of Electron Cloud Density By Microwave Transmission

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Summary

- Physical principles of the measurement method.
- How to make the measurement in practice.
- Experimental setup on the CesrTA
- Measurement results.
- Cyclotron resonances.
- Future Plans

Wide Range of Application

The Microwave transmission method was initially developed by F. Caspers and T. Kroyer at CERN (ECLOUD'04).

Besides the **PEP-II Low Energy Ring** and **Cesr-TA** the method has also been used on other machines:

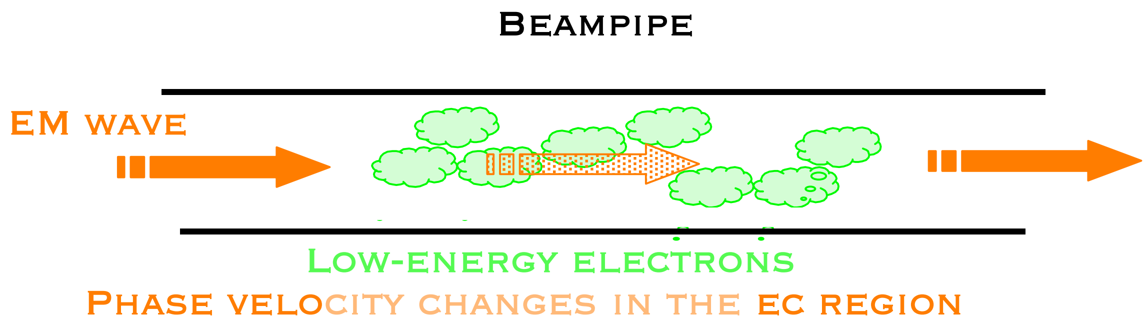
- **I. Kourbanis**
- **R. Zwaska**

} *Tevatron MI (planned)*

- **F. Caspers**
- **T. Kroyer**

} *SPS*

Measurement by microwave transmission



Propagation through the electron plasma introduces an additional term to the standard waveguide dispersion:

$$k^2 = \frac{\omega^2 - \omega_c^2 - \omega_p^2}{c^2}$$

Plasma frequency $2c(\pi\rho_e r_e)^{1/2}$

Beampipe cut-off frequency

The presence of the "electron plasma" affects the propagation of the wave, while there is essentially no interaction with the ultrarelativistic beam.

Induced additional phase delay

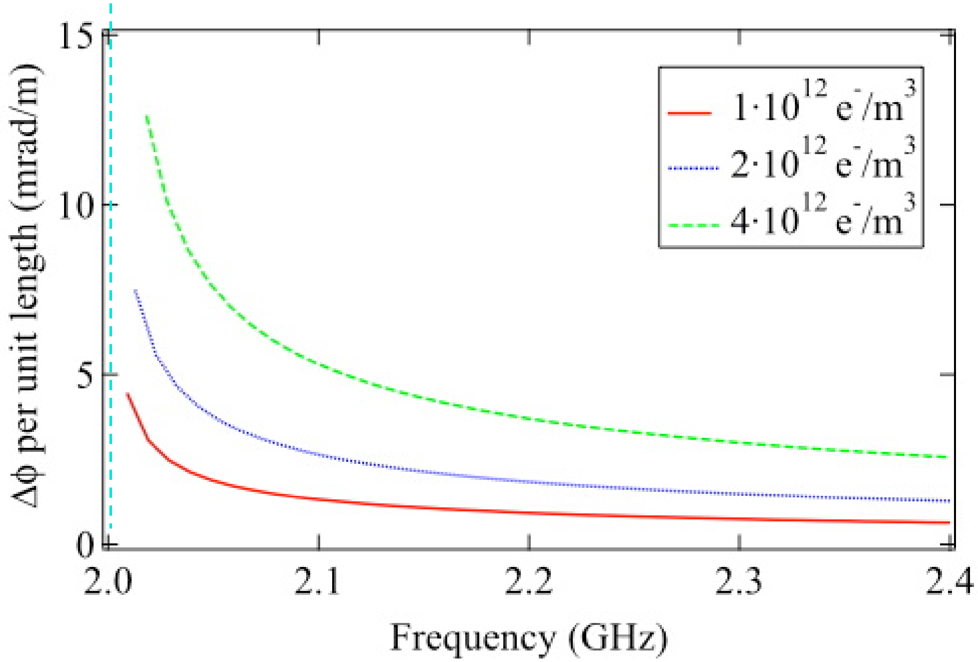
The resulting phase shift per unit length is:

By measuring → $$\frac{\Delta\varphi}{L} = \frac{\omega_p^2}{2c(\omega^2 - \omega_c^2)^{1/2}}$$ ← ...one calculates

and

$$\rho_e \approx \frac{f_p^2}{80} \; (e^- / m^3)$$

Beampipe cut-off



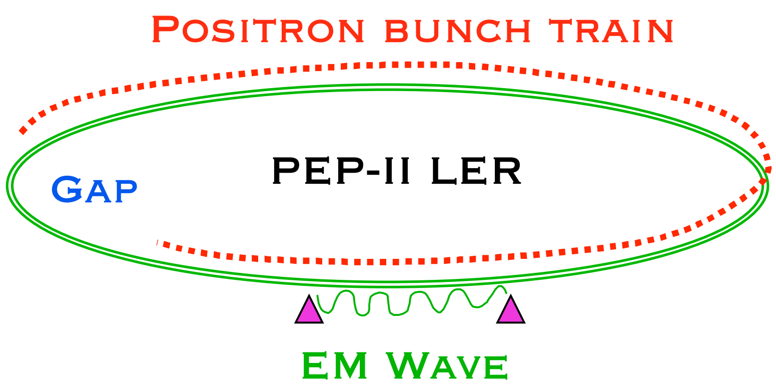
Frequencies closer to cut-off experience larger phase shifts. Their attenuation is generally larger in actual beampipes, though.

Formulas valid only when B=0

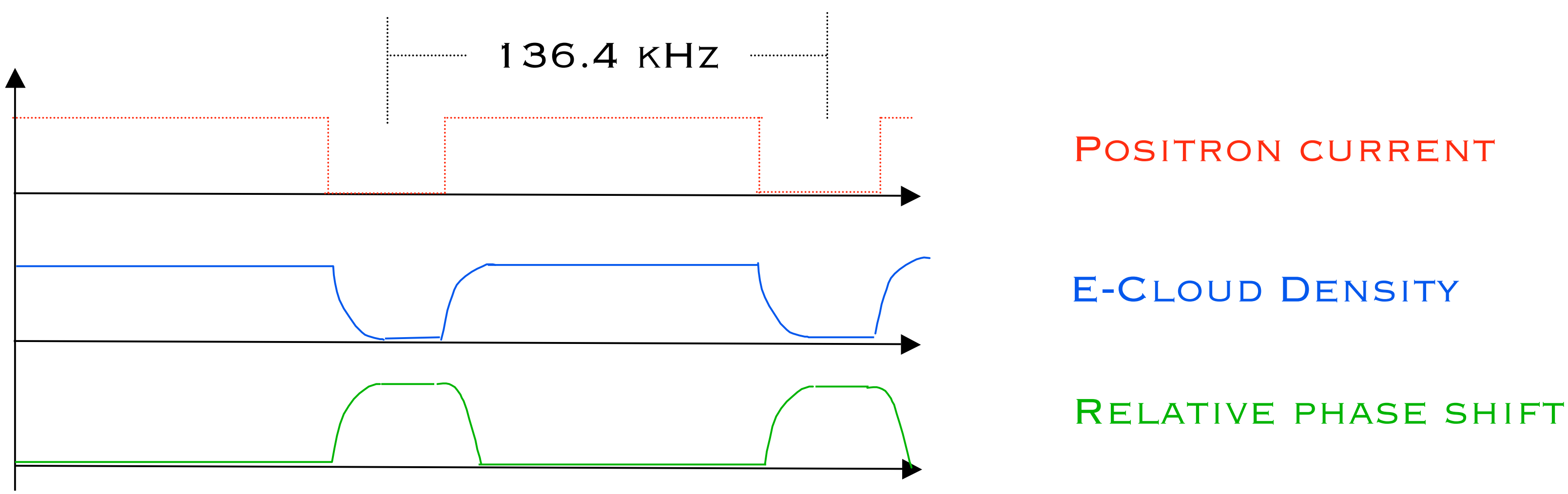
Practical Difficulties

- Low phase shift values (few mrad). Can we increase it ?
  - Frequency closer to beampipe cut-off ⇔ higher attenuation
  - Longer propagation distance ⇔ higher attenuation
- Noisy environment: direct beam signals !
- BPM not optimized for TE-wave transmission/reception.
  - Typical Tx/Rx losses > -60 dB
- Temperature related phase shift (beam on, beam off).

Phase Shift Time Dependence



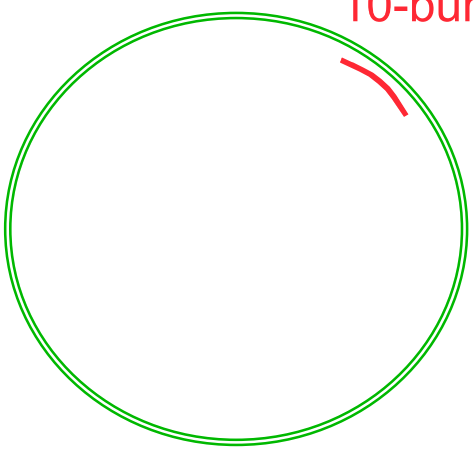
Gap length ≈ 100 ns
Revolution period ≈ 7.3 μs
Bunch spacing ≈ 4 ns



The phase shift changes at a frequency equal to the (gap) revolution frequency !!!

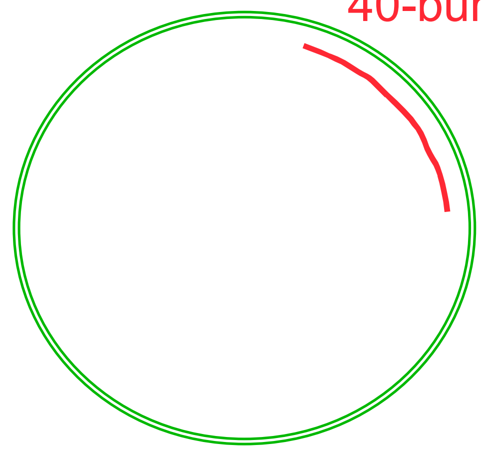
CesrTA Fill Patterns (e^+/e^-)

10-bunch train

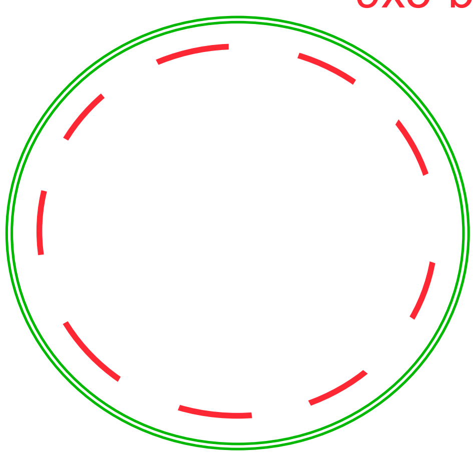


Energy = 2 - 5.2 GeV
Gap length ≈ 210 ns - 2.4 μs
Revolution frequency ≈ 390 kHz
Bunch spacing ≈ 14 ns

40-bunch train



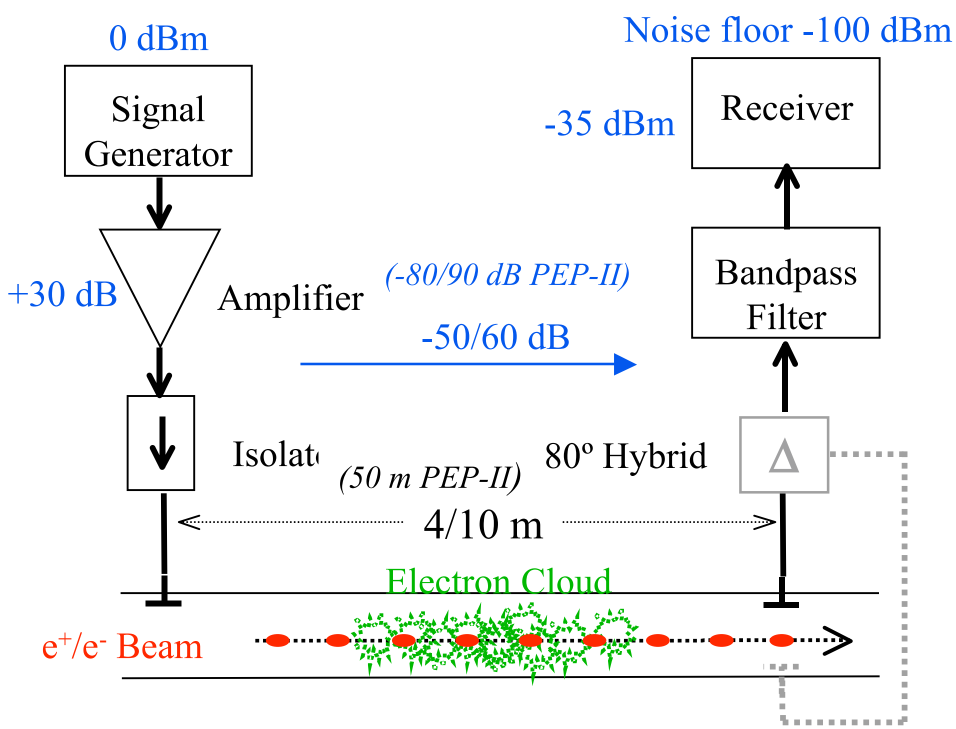
9x5-bunch trains



A greater flexibility in the fill pattern choice is available on Cesr-TA

in this case the gap revolution frequency is 9 x f_{rev}

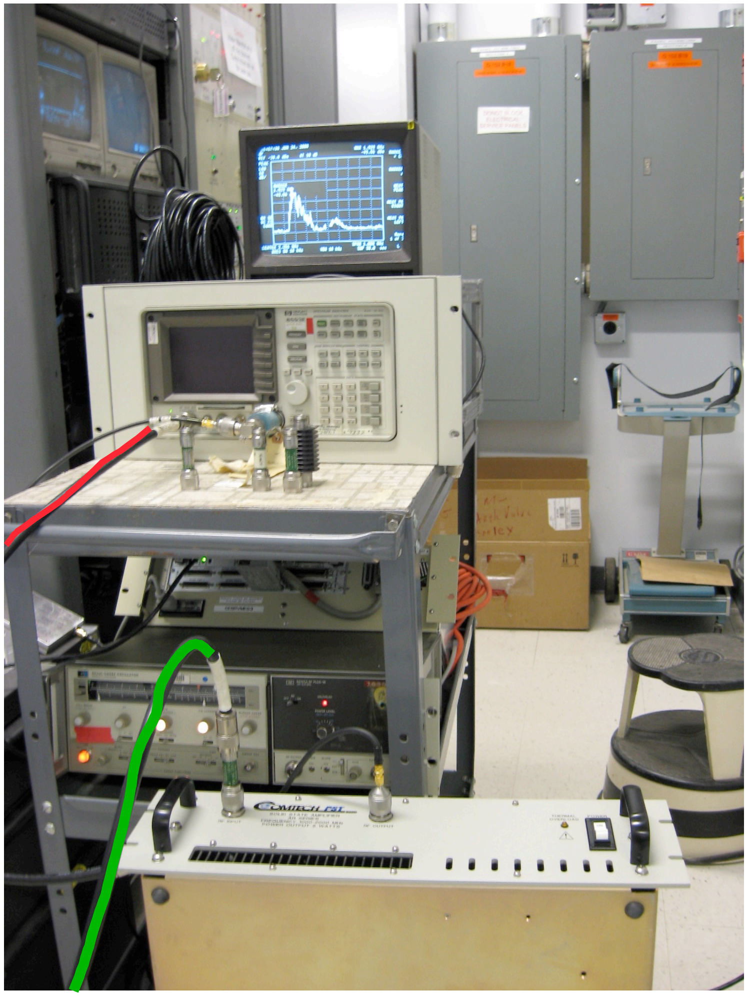
Experimental Setup (Cesr-TA)



CesrTA dipole/ex-wiggler

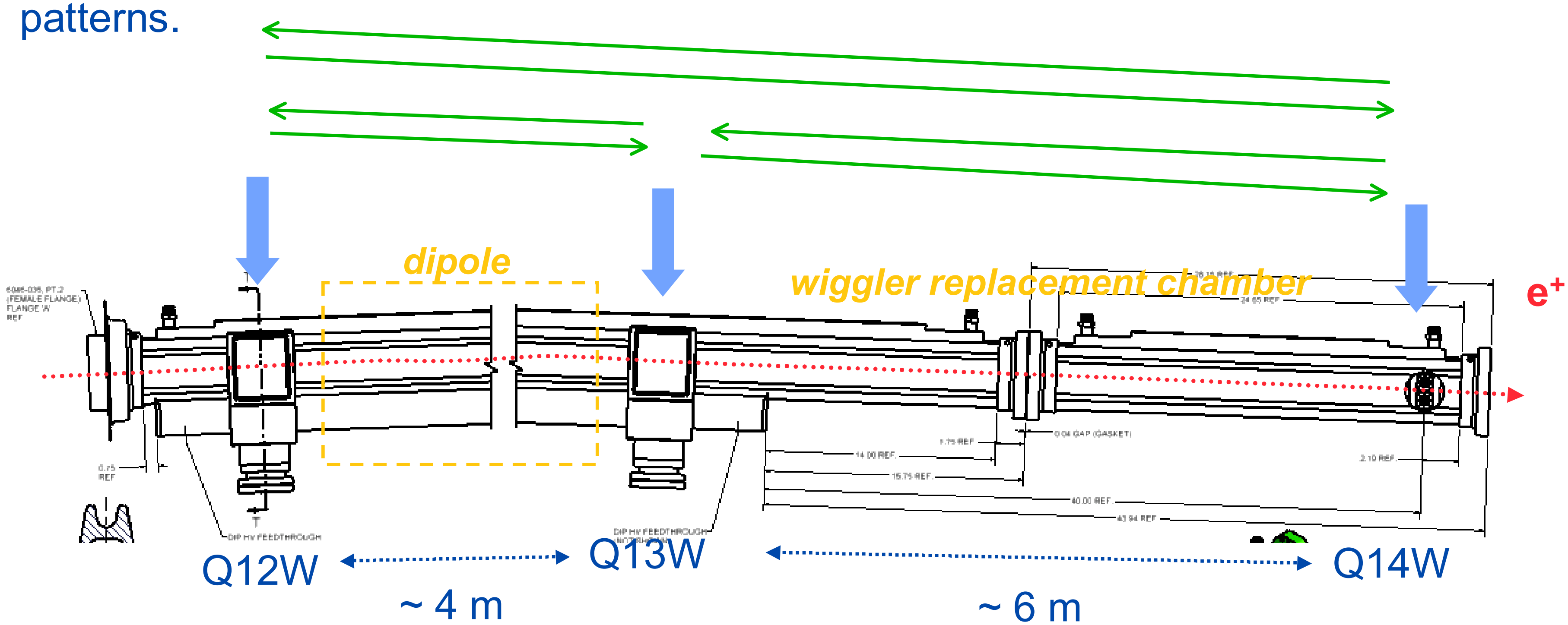
- The hybrid used on PEP-II was not necessary on Cesr (higher SNR).
- A BPF is used to further reduce beam power on the receiver. Total received power < 100 mW.
- The 20 dB isolator protects transmitter and amplifier.
- Transmission attenuation is around 50/60 dB, with a 60+ dB SNR at the receiver.

Experimental Setup

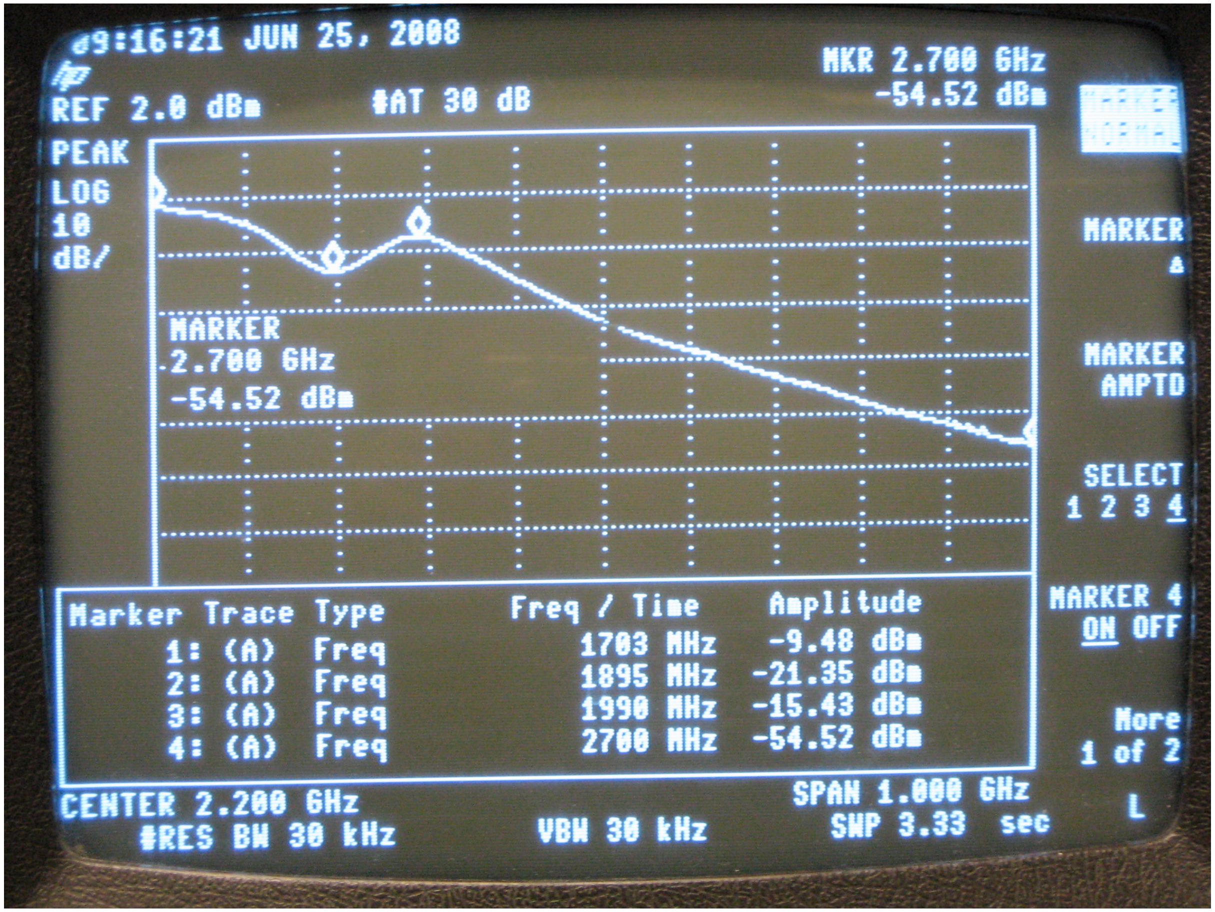


Transmitter/Receiver Positions

We had 3 BPM available for the measurement, to be used either as transmitting or receiving port.
By trying all the possible combination, we were able to test the effects of different vacuum chambers, different propagation lengths, and different propagation direction between e^+ or e^- beam and TE wave.
The measurements were taken at both 2.0 and 5.2 GeV, with a variety of fill patterns.



Closed-loop Transfer Function (cables)



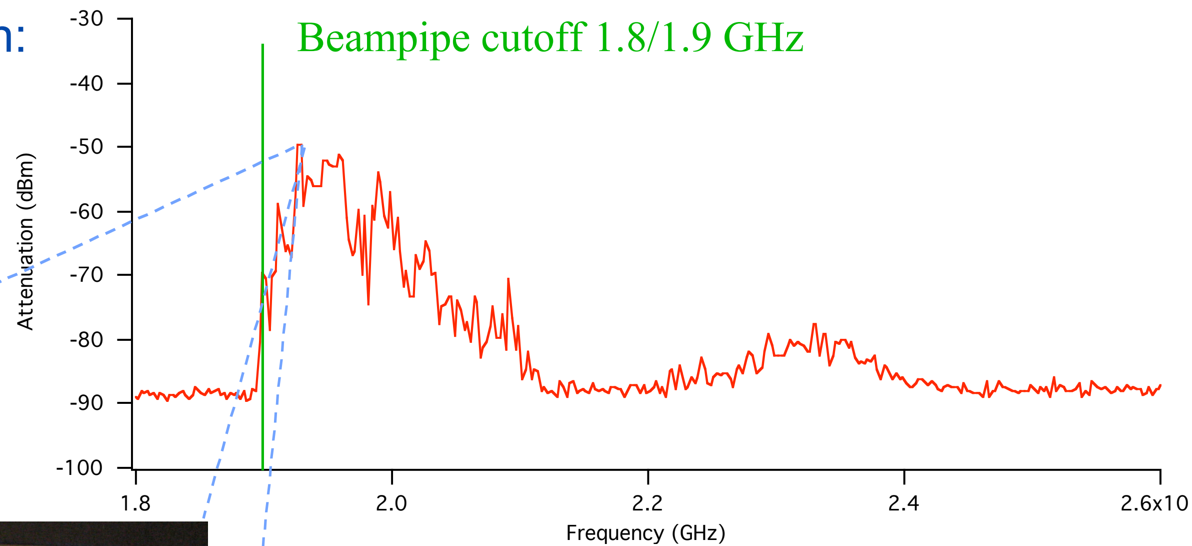
Includes: cables, receiver, amplifier

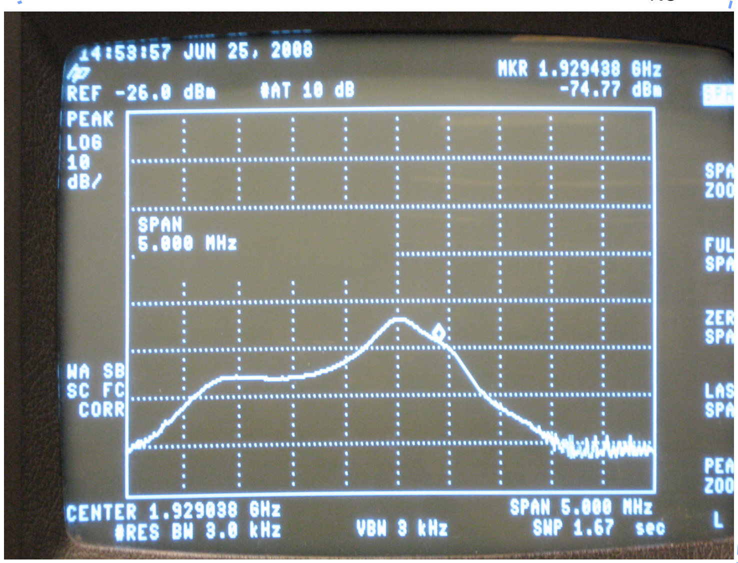
This data can be used for signal equalization

Beampipe Transfer Function

Choice of measurement region:

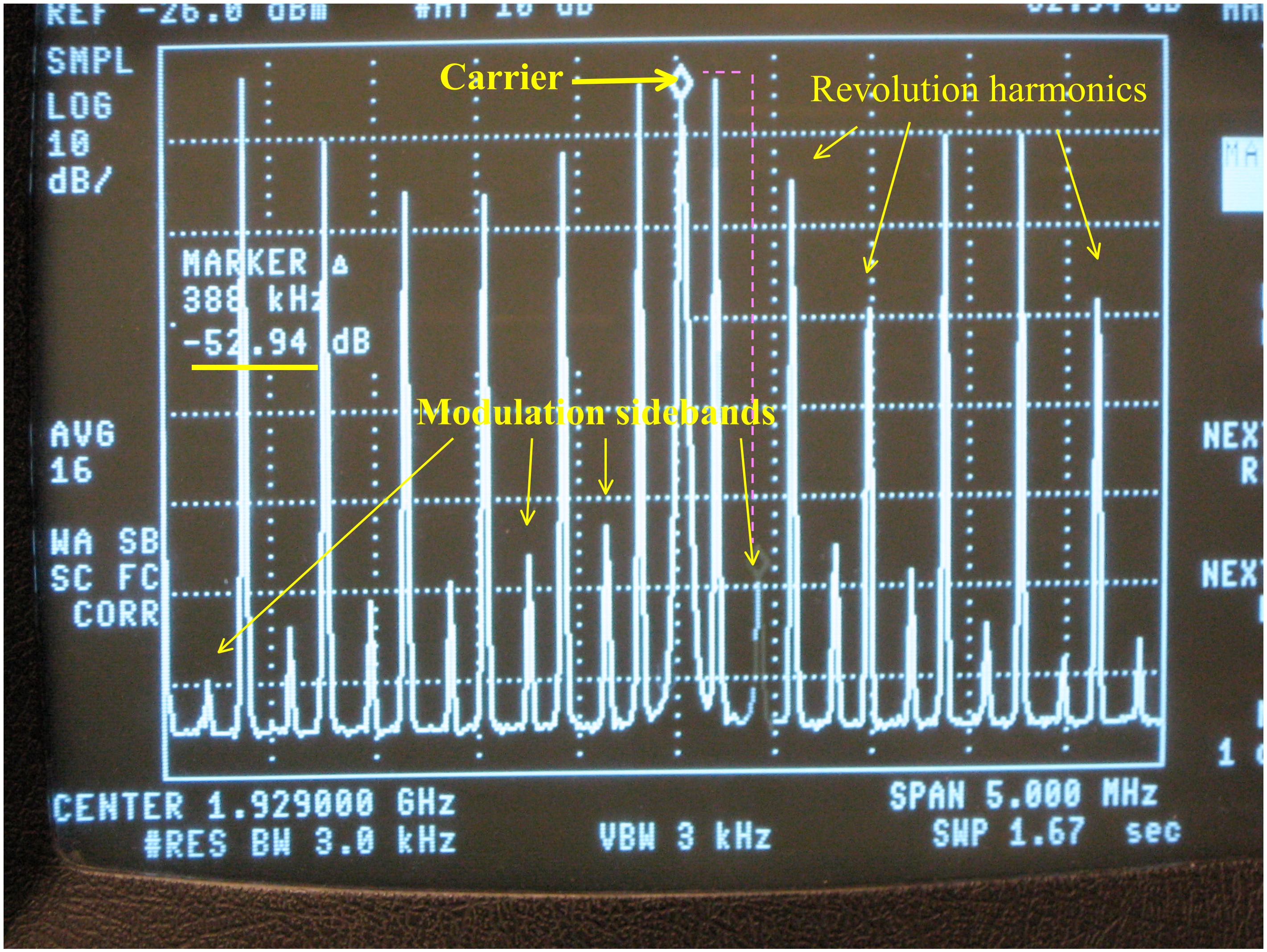
- Close to cutoff
- Low attenuation
- Reasonably “flat”





Search for origin of reflections and/or resonances in the beampipe did not turn out conclusive results (gate valves, pumping holes, RF cavity)

Received Signal



Phase Modulation

The *periodic clearing of the electron cloud* by the gap, when it passes between our Tx and Rx BPM's *phase modulates the transmitted signal*:

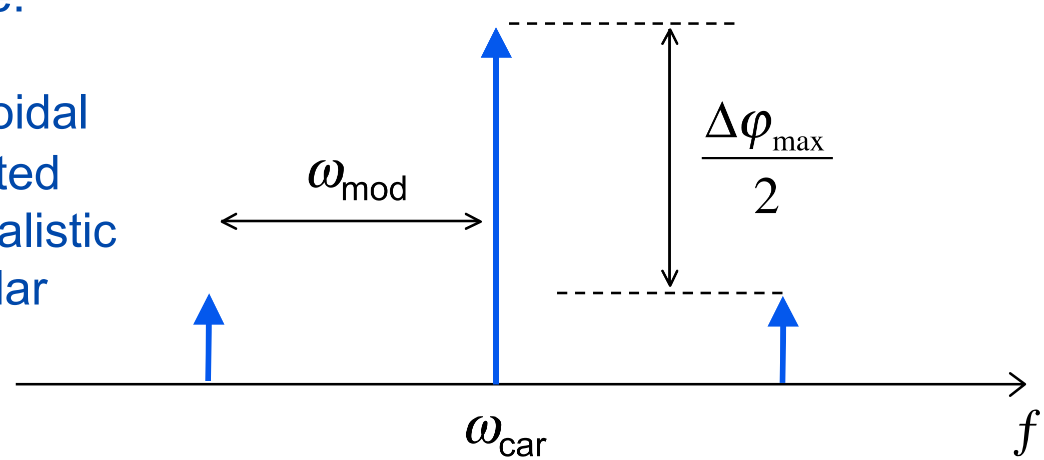
$$s(t) = A\cos[\omega_{car} t + \Delta\varphi(t)]$$

- What happens if the gap is not long enough to completely clear the electrons ?
- What happens if the gap is shorter than the distance between Tx and Rx ?

Amplitude modulation ? (Caspers)
At very low modulation depth AM and PM are undistinguishable.

$\beta = \Delta\varphi/2$ is valid only for sinusoidal modulation. We have calculated correction factors for more realistic modulating signals (rectangular wave, sawtooth,…)

If $\Delta\varphi(t) = \Delta\varphi_{max}\sin(\omega_{mod} t)$



Measurements at CesrTA

- Compare positron and electron beam
  - *Build-up of low-energy electrons has also been observed with an electron beam.*
- Compare measurements with TE wave propagating in the same and in the opposite direction of the beam.
- Dependence on gap length and beam/bunch current
- Effects of different vacuum chamber shapes
  - *Arc and wiggler replacement pipes.*
- Dependence on beam energy
  - *More photoelectrons generated in the dipole at 5.2 GeV*
- Cyclotron resonance
  - *Dipole field is 792 G at 2 GeV,* f_{cycl}*=2.22 GHz*

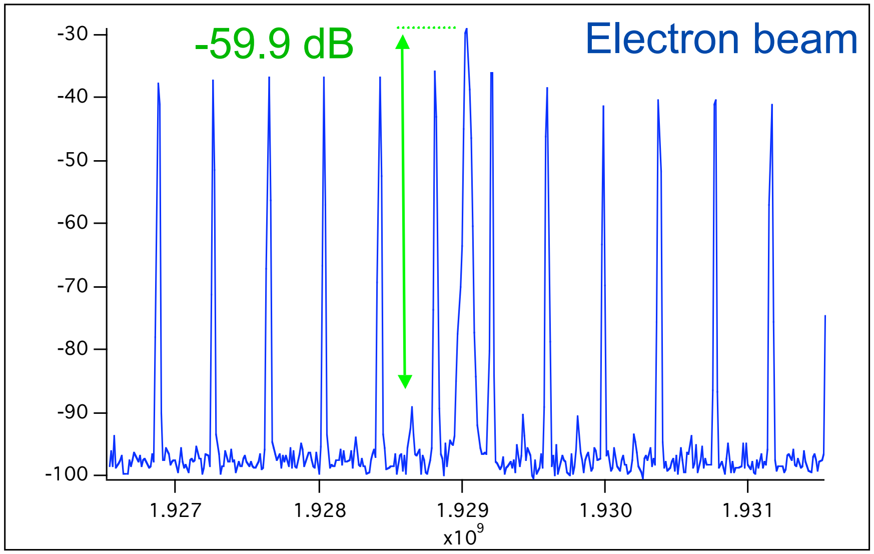
Electron vs. Positron Beam

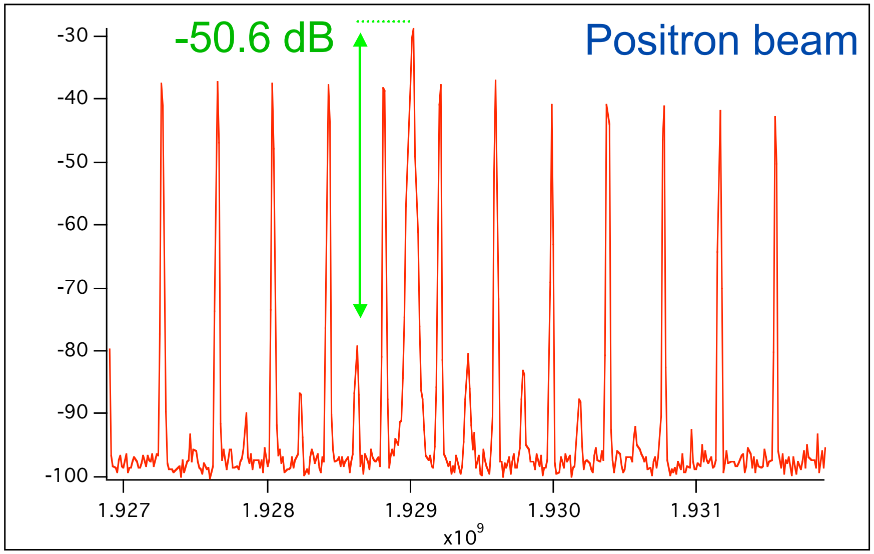
2 GeV - Dipole region (Q12W-Q13W) 10 bunches x 1 mA

Difference in the relative sideband amplitude between electron and positron beam, in otherwise identical machine conditions.

The low-energy electron density in the presence of a positron beam has a ~3 times higher value than with an electron beam.
This effect is due to the multiplication of secondary electrons caused by resonant interaction of beam and e-cloud.

Systematic comparison of the dependance of ECD on beam current between e^+ and e^- beams.





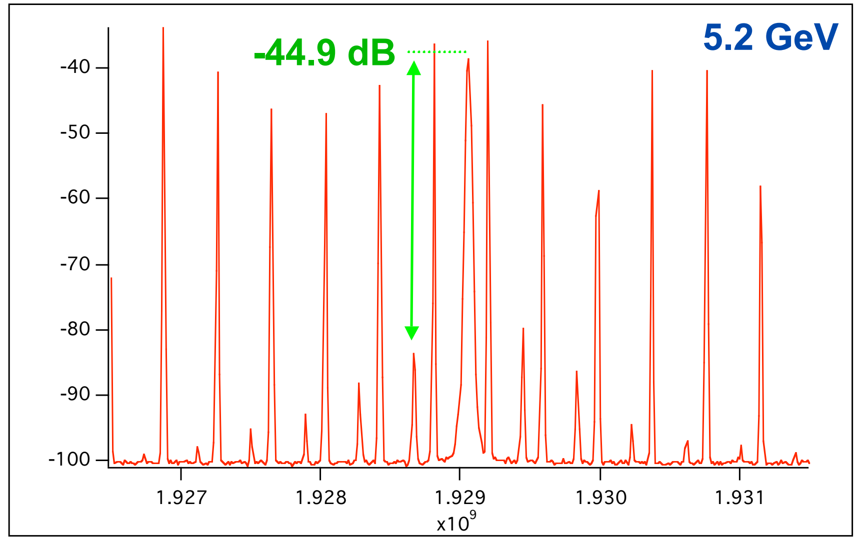
2 Gev vs. 5.2 Gev Measurements

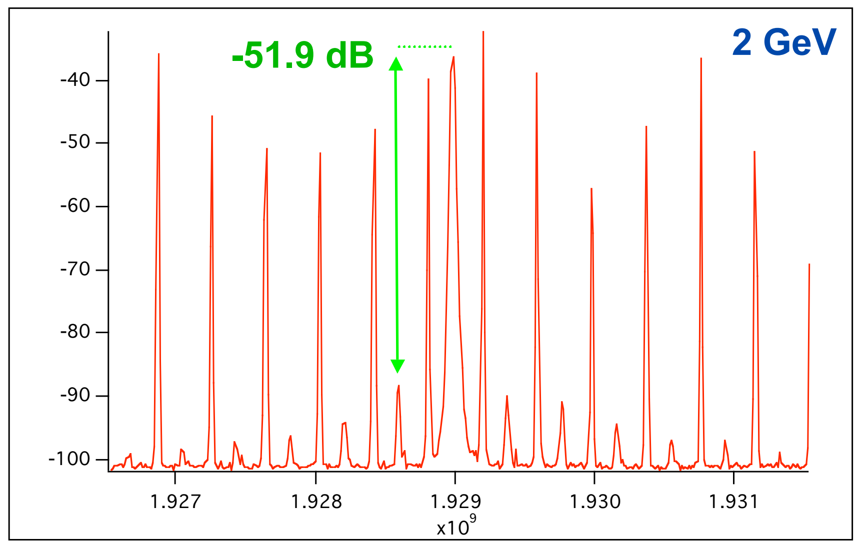
Ex-Wiggler region (Q13W-Q14W) 10 bunches x 1 mA

Difference in the relative sideband amplitude between two different beam energies (positron beam).

At higher beam energy the enhanced production of photoelectrons increase the low-energy electron density by a factor greater than 2.

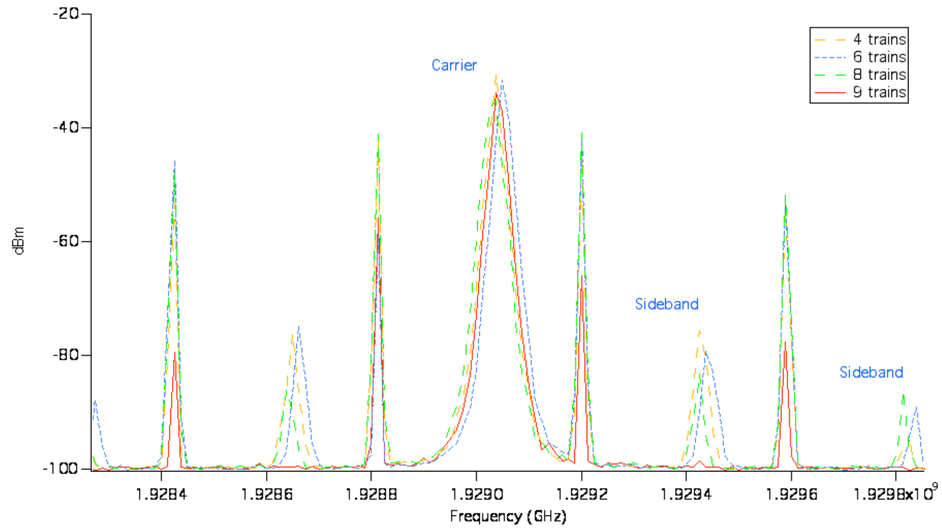
Validate dependance on beam energy in theoretical models of the e-cloud.





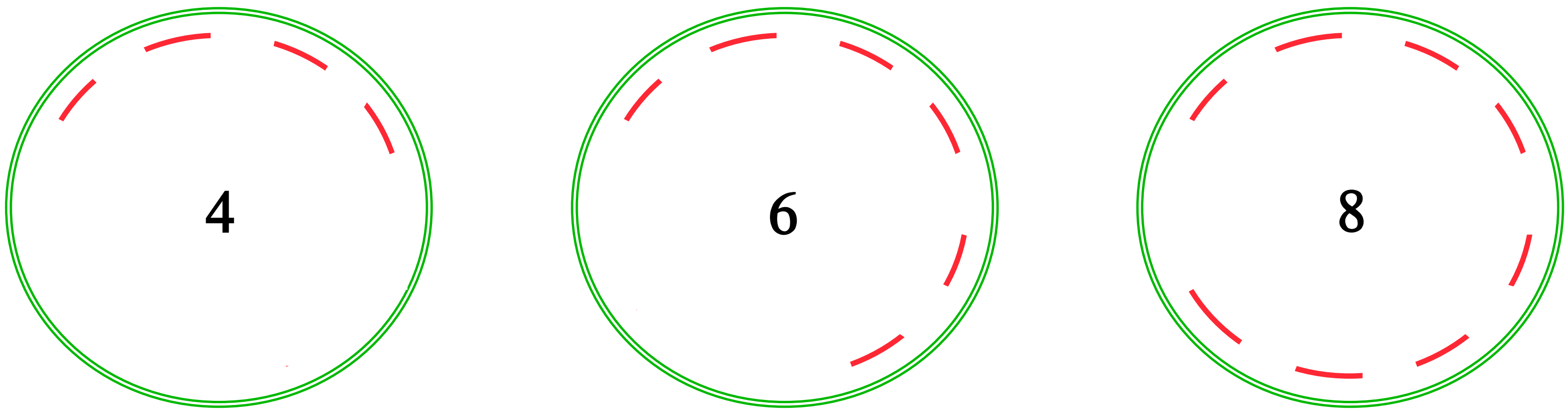
E-Cloud Rise/Fall Times

Ex-Wiggler region (Q14W-Q13W) 45 bunches x 1 mA



"Macro-trains" of variable length were used to detect saturation in the ECD growth. Flat top in the ECD translates into constant depth of modulation.

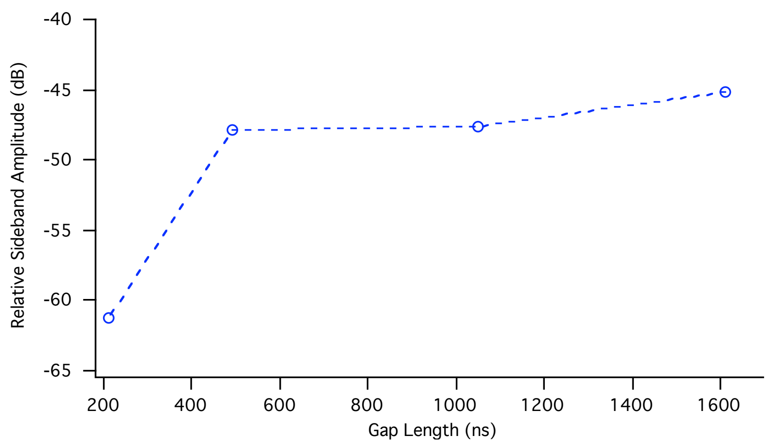
More experimental data is needed.

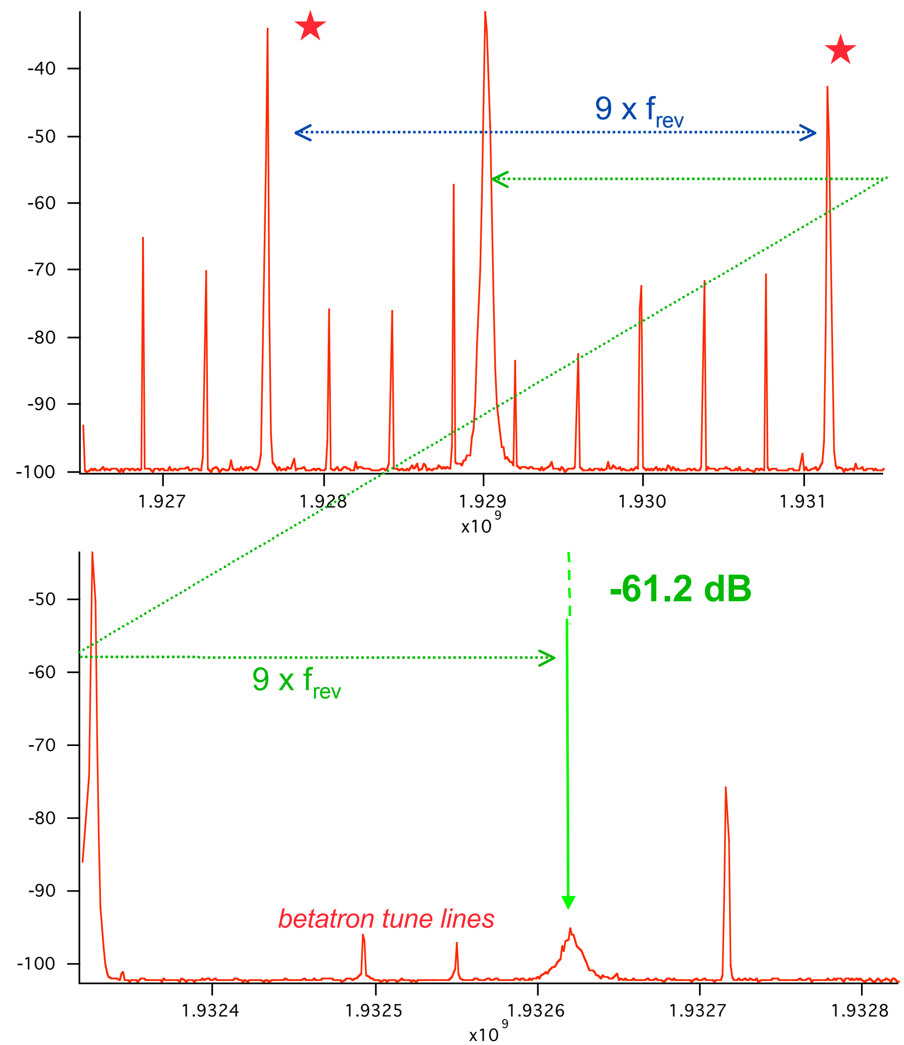


9 x 5 Bunch Fill Pattern

Ex-Wiggler region (Q14W-Q13W) 45 bunches x 1 mA

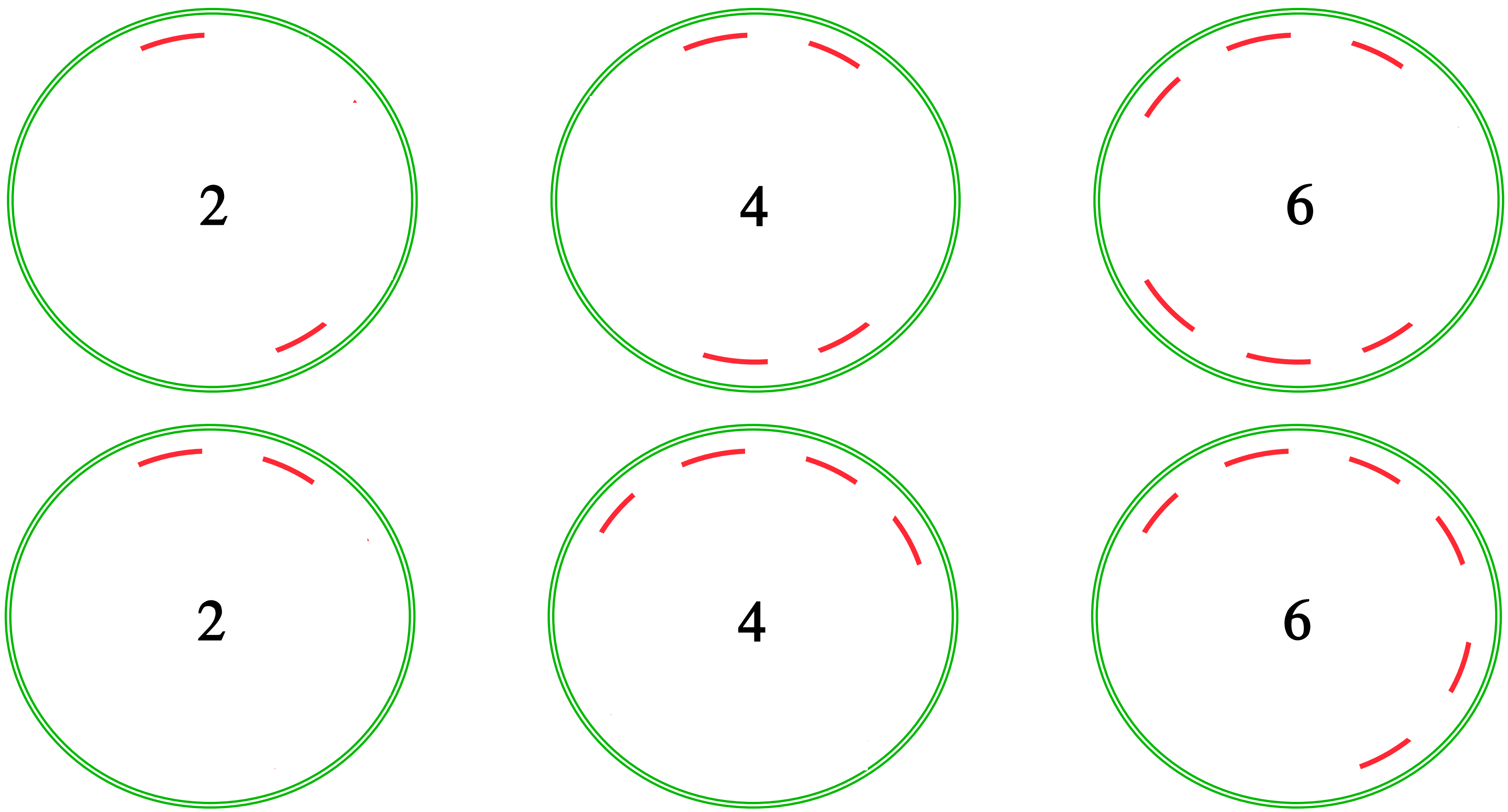
Effects of the train periodicity are evident (enhancement of the ninth revolution harmonic ★).
Although total current is higher (45 vs. 10 mA). The much shorter gap (210 ns) induces a much smaller modulation depth. The ninth sideband is also enhanced.



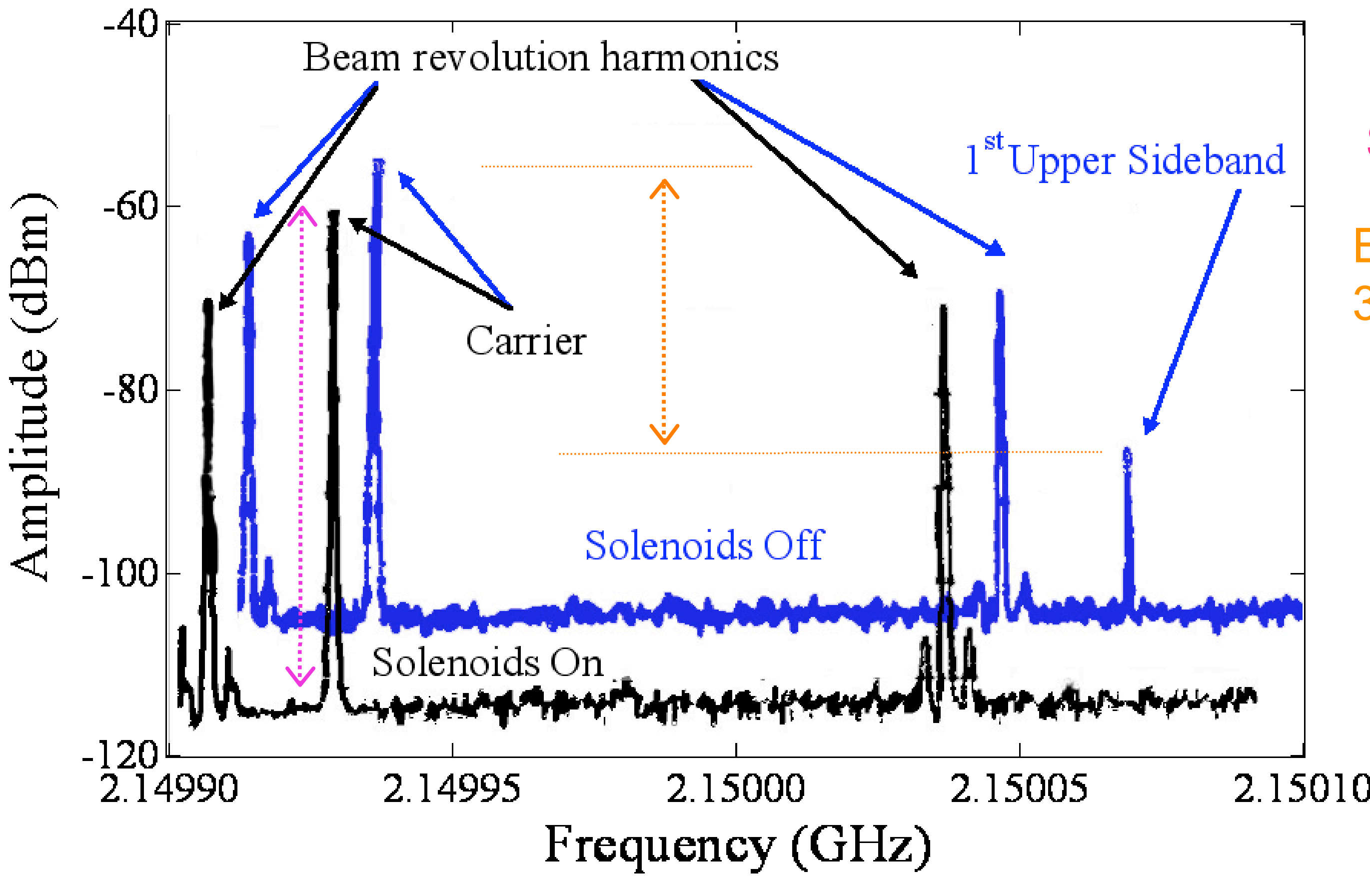


Alternative fill patterns for future experiments

These patterns allow to study different train/gap lengths at constant total current. Additionally, the electron beam signal can be used for normalization.



Clearing Solenoids (PEP-II)

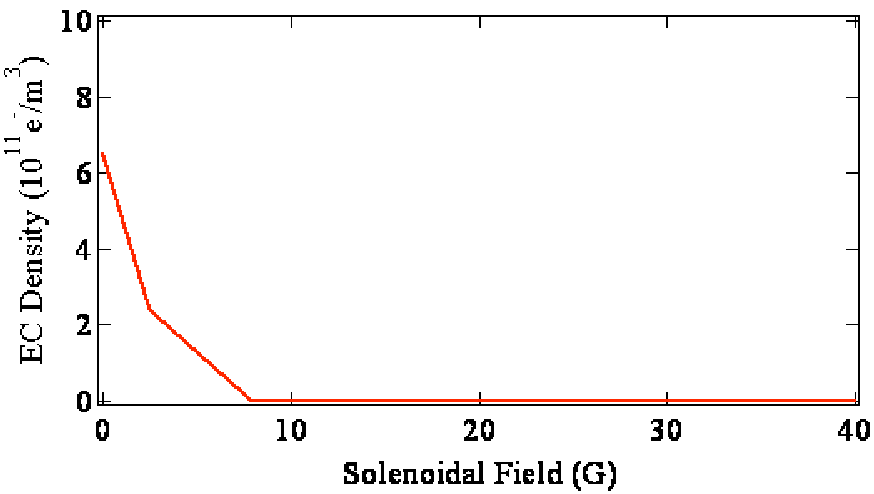


SNR: 50 dB

ECD resolution: $3 \cdot 10^{10}$ e^-/m^3

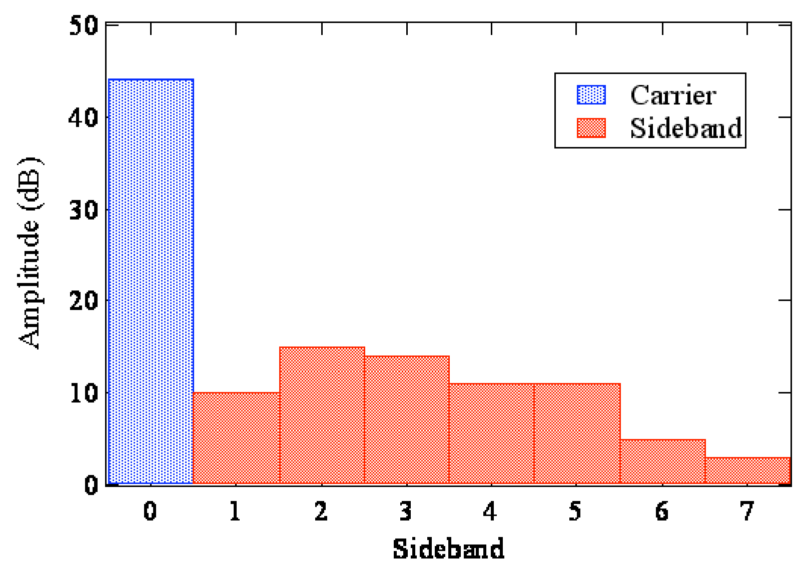
Although the time evolution of the e-cloud density is not simply sinusoidal, the simple model already gives results in good agreement with other estimates (codes)

Experimental Results (PEP-II)

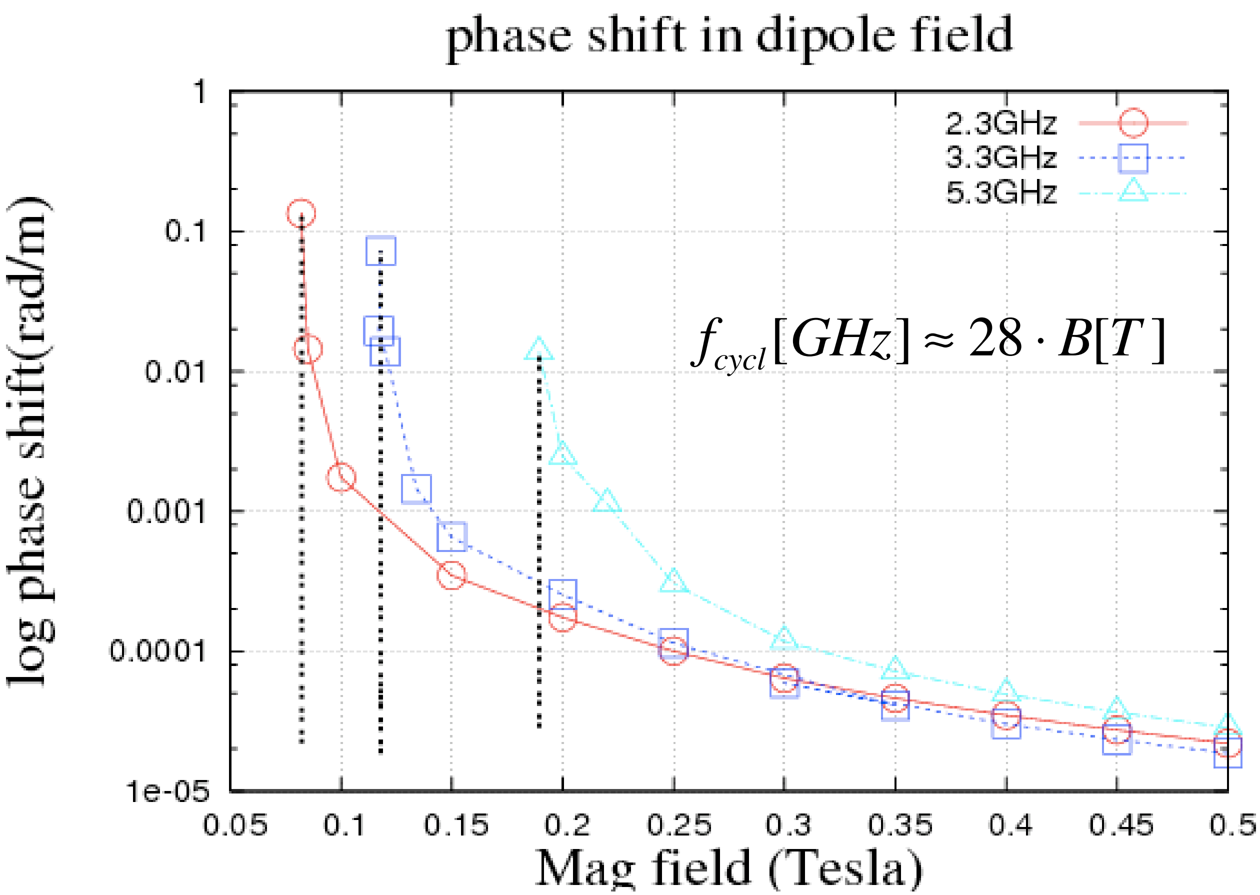


Excellent tool for studying the efficiency of any e-cloud clearing scheme.

Multiple sidebands linked to the bandwidth of modulation process (Carson's rule). Complete demodulation yields the ECD time evolution.



Cyclotron Resonance

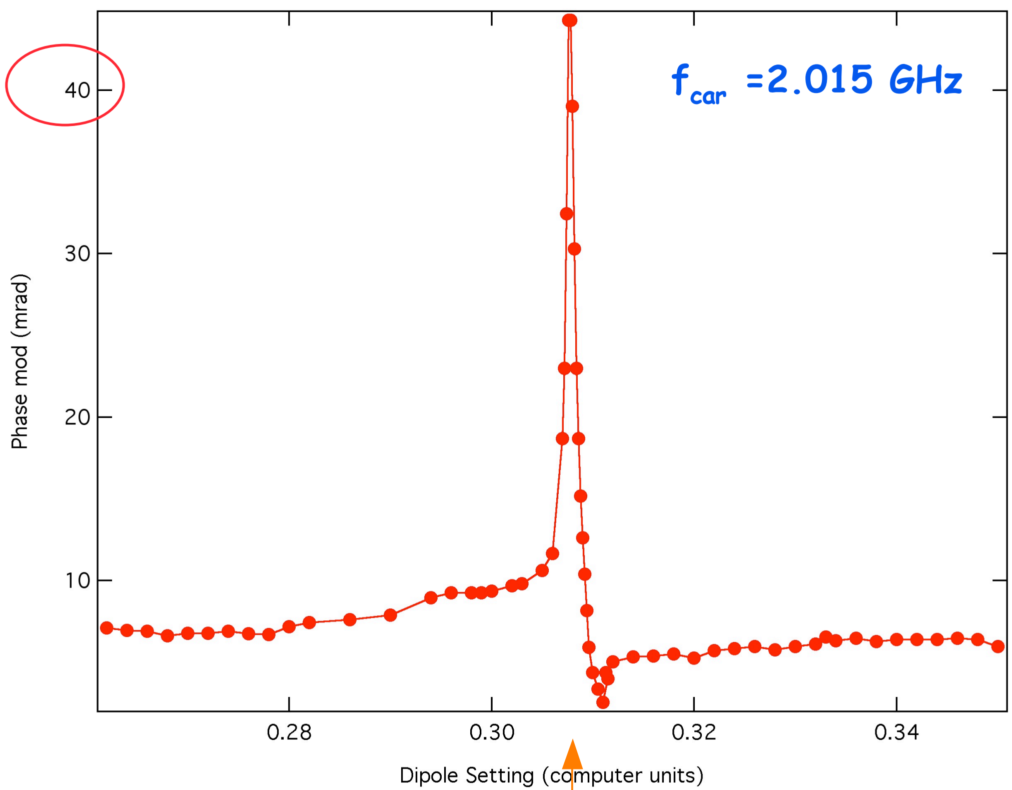


But what is the relationship between this phase shift and the e-cloud density ?
Are we measuring the ECD, or rather the magnetic field strength ?

Cyclotron Resonance Measurement

Unequivocal measurement of a cyclotron resonance

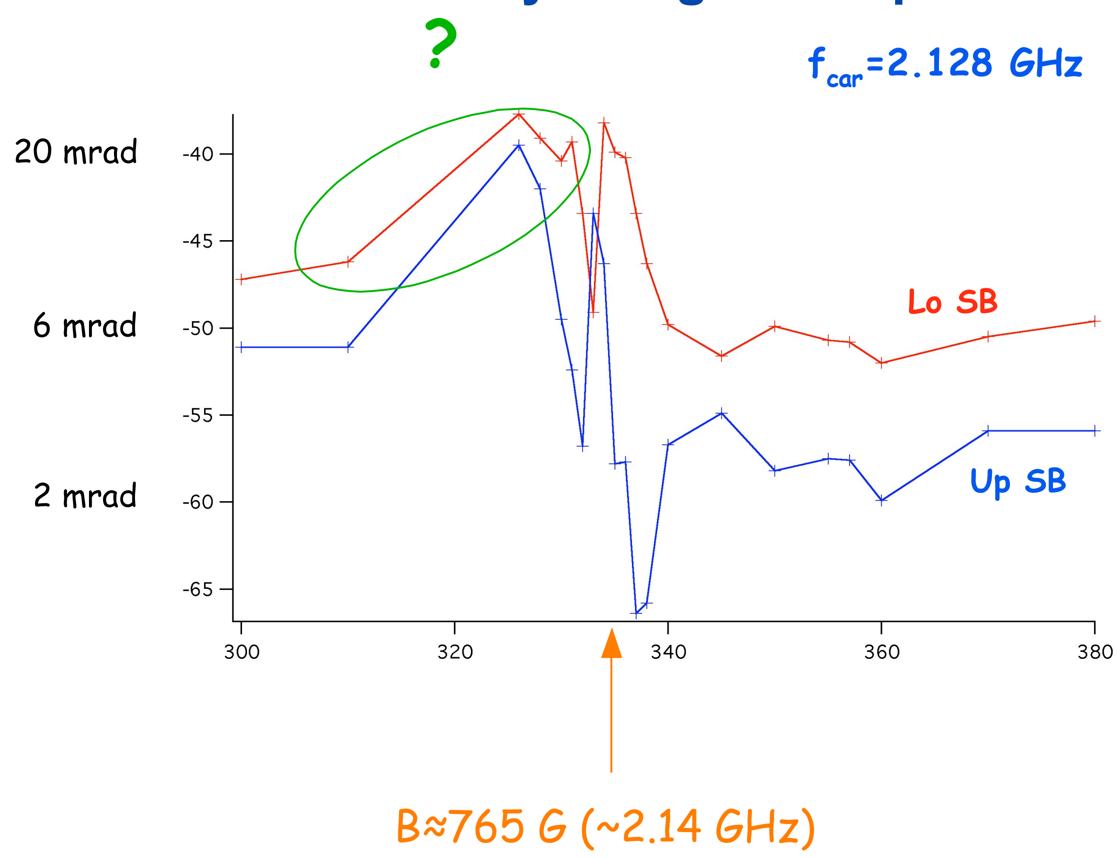
40+ mrad over a length of only 4 meters !



B≈700 G (~1.96 GHz)

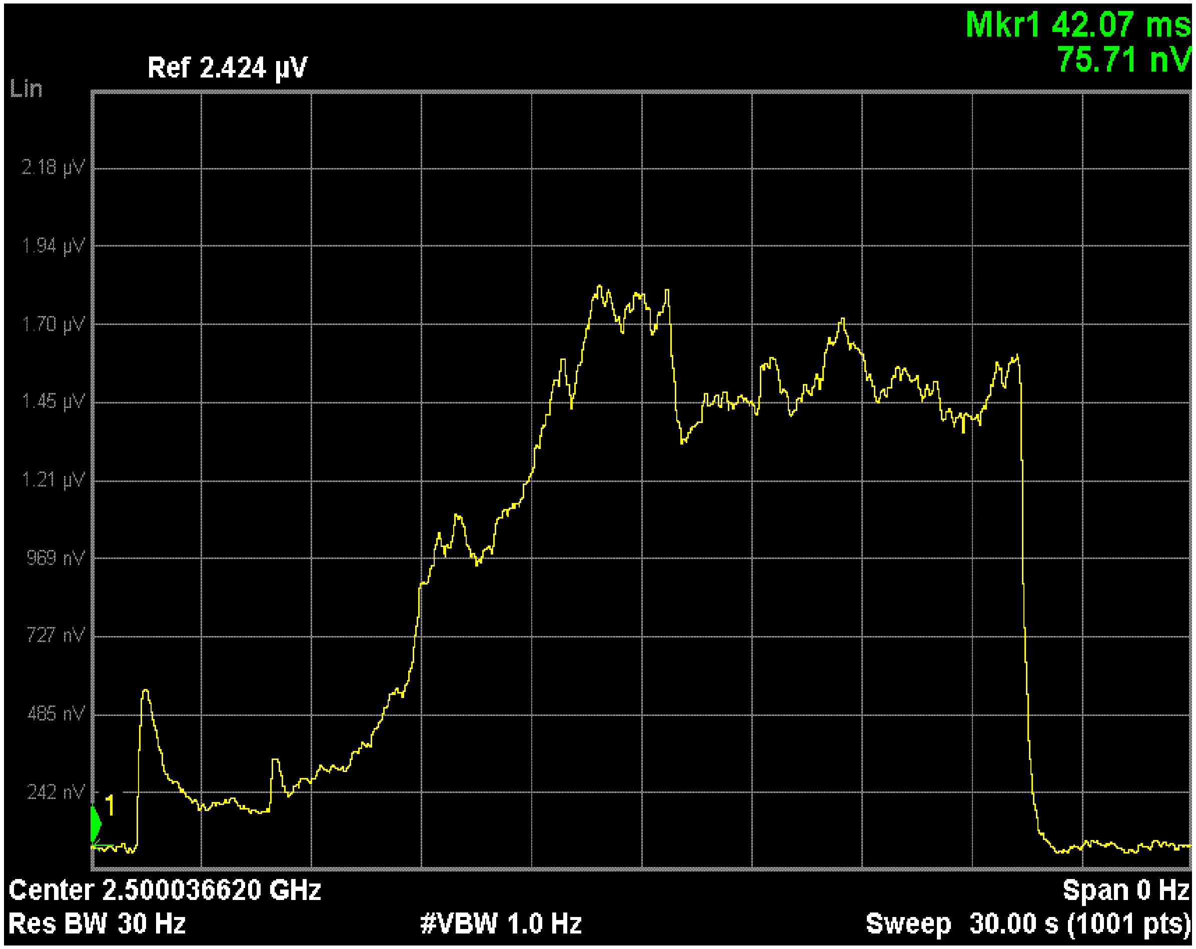
More Experimental Results

Difference between upper and lower sideband evidence of AM/PM mod. The analytical model is currently being developed.



Time Resolved Measurements

Caspers, et al. SPS 2008 - Maximum time resolution ~100 μs



Future Activities

- How to improve the measurements ?
  - Better hardware. Bigger amplifier ?
  - From BPM's to dedicated couplers optimized for TE mode.
- More beamtime
  - CesrTA (cyclotron resonance, time domain measurements)
  - Main Injector, KEK-B ?, DAΦNE ?
- Better understanding of cyclotron resonances
  - More analytical work and modelling
- Development of a dedicated receiver
  - Full demodulation of received signal (software, hardware)